First Avalanche-photodiode Camera Test (FACT): A novel Camera using G-APDs for the Observation of very high-energy γ-Rays with Cherenkov Telescopes

I. Braun [a], S.C. Commichau [a,*], M. Rissi [a,1], M. Backes [b], A. Biland [a], T. Bretz [c], I. Britvitch [a], V. Commichau [a], H. von Gunten [a], D. Hildebrand [a], U. Horisberger [a], D. Kranich [a], E. Lorenz [a,d], W. Lustermann [a], K. Mannheim [c], D. Neise [b], F. Pauss [a], M. Pohl [e], D. Renker [f], W. Rhode [b], U. Röser [a], U. Straumann [g], G. Viertel [a]

[a] *ETH Zurich, CH-8093 Zurich, Switzerland*
[b] *Dortmund University of Technology, D-44221 Dortmund, Germany*
[c] *University of Würzburg, D-97074 Würzburg, Germany*
[d] *Max-Planck-Institut für Physik, D-80805 München, Germany*
[e] *University of Geneva, CH-1211 Geneva, Switzerland*
[f] *Paul Scherrer Institut (PSI) Villigen, CH-5232 Villigen, Switzerland*
[g] *University of Zurich, CH-8057 Zurich, Switzerland*

Abstract

We present a project for a novel camera using Geiger-mode Avalanche Photodiodes (G-APDs), to be installed in a small telescope (former HEGRA CT3) on the MAGIC site in La Palma (Canary Island, Spain). This novel type of semiconductor photon detector provides several superior features compared to conventional photomultiplier tubes (PMTs). The most promising one is a much higher photon detection efficiency.

Key words: Extensive air showers, Gamma-ray, Geiger-mode avalanche photodiodes, Solid-state photon detectors, Air Cherenkov telescope
PACS: 96.50.sd, 95.85.Pw, 85.60.Dw, 29.40.Wk

1. Introduction

The observation of cosmic sources emitting very high-energy (VHE) γ-rays (0.1 - 100 TeV) by large Imaging Air Cherenkov Telescopes (IACTs) has opened a new window in Astronomy. Impressive new results from galactic and extragalactic sources have been obtained during the past four years with the MAGIC [1], H.E.S.S. [2], VERITAS [3] and CANGAROO [4] experiments, demonstrating that the VHE γ-ray sky is much richer than previously expected.
The heart of an IACT is the light detection system, i. e. an imaging camera comprising a matrix of high-efficiency photon detectors augmented by so-called light catchers and readout electronics. A crucial design parameter is the Photon Detection Efficiency (PDE), i.e. the conversion efficiency of photons into measurable photoelectrons. Recently, a novel type of semiconductor photon detector has been developed, the so-called Geiger-mode Avalanche Photo-

* Corresponding author. Tel.: +41-44-63 32185; fax.: +41-44-63 31104
Email address: commichau@phys.ethz.ch (S.C. Commichau).
[1] Also for correspondence.

diode (G-APD) (for a review see Ref. [5]). G-APDs are considered as a replacement for conventional PMTs as the former offer a substantially higher PDE. These new devices promise an important step forward to an improved imaging camera.

Fig. 1. A photomontage of the refurbished HEGRA CT3 telescope with $\sim 13\,\mathrm{m}^2$ mirror area (La Palma, Canary Islands, Spain).

A G-APD-based prototype camera is currently being developed by a collaboration of Swiss and German institutes. The camera will be tested under realistic conditions using the refurbished HEGRA CT3 telescope (Fig. 1) or an equivalent mount [6].

2. Scientific Prospects

The project presented herein addresses several technical and scientific topics:

- Test of the first G-APD-equipped imaging camera under realistic conditions.
- Long-term monitoring of nearby, bright blazars at very high energies [6].
- Search for orbital modulation of the blazar emission from supermassive black hole binaries.
- Studies of flares on short time scales and search for their physical origin.
- To trigger follow-up observations with higher sensitivity with IACTs that are currently in operation.
- Joint observations with the Whipple monitoring telescope for an extended time per day [6].
- To carry out multi-messenger observations together with the IceCube neutrino detector.

3. G-APDs as Photodetectors for IACTs

G-APDs may potentially replace conventional photomultiplier tubes (PMTs) as they provide several attractive features [5], like an excellent single photon resolution, a high PDE, a low operation voltage ($< 100\,\mathrm{V}$) and robustness, i.e. there is no aging due to starlight or damage if accidentally exposed to daylight when under bias. These features make G-APDs easier to handle than PMTs in typical operating conditions for IACTs. The main improvement compared to conventional PMTs is expected due to the increased PDE, which lowers the achievable energy threshold of an IACT for a given mirror area. Apart from that, G-APDs provide a very reproducible output signal per photoelectron (Fig. 2).

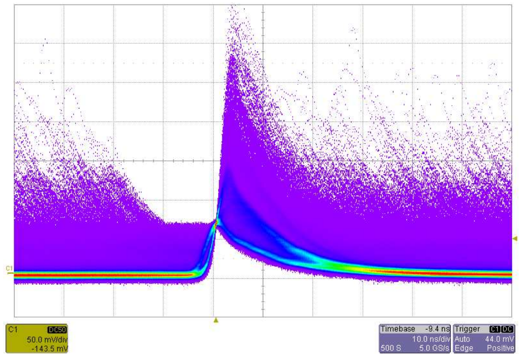
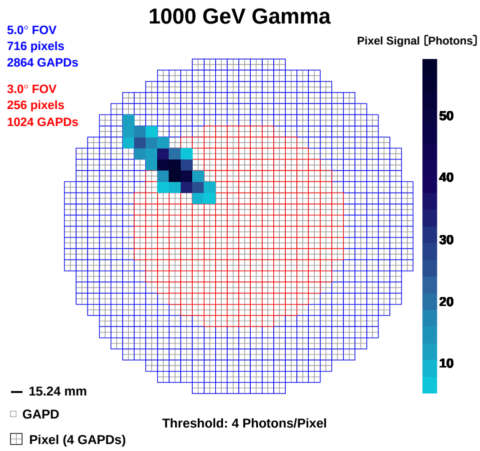


Fig. 2. Superposition of G-APD noise signals (after amplification). Horizontal scale: 10 ns/div., vertical scale: 50 mV/div..

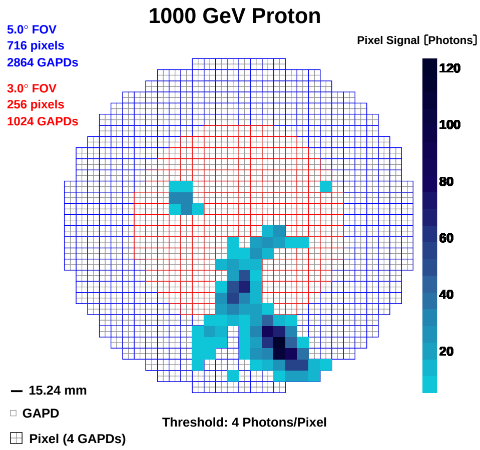
The G-APD selected for the camera project (Hamamatsu MPPC S10362-33-100C [7]) has a dimension of $3 \times 3\,\mathrm{mm}^2$ comprising 900 pixels of $100 \times 100\,\mu\mathrm{m}^2$ size housed in a ceramic casing. The fill factor is 78.5 %, the PDE is $\sim 50\,\%$ for a wide range of wavelengths, the dark count rate is $\mathcal{O}(10^6)$ counts per second and the internal gain is $\sim 2 \cdot 10^6$ at nominal operating voltage.
Several successful small tests were performed in the laboratory and in the field in order to evaluate G-APDs as a replacement for PMTs in IACT cameras [8–10]. The results are promising and provide evidence that G-APDs would more than double the sensitivity of IACTs currently equipped with conventional PMTs [9,10].

4. Camera Layout and Baseline Design

For the scientific program outlined above, the construction and design of the novel G-APD camera has to meet stringent requirements. First of all, shower images in the TeV-energy range have to be fully contained in the camera. As an example, Fig. 3 shows a MC-simulated γ-ray (a) and a proton shower image (b) in a camera of two different diameters corresponding to a FoV of 3° and 5°, respectively.



(a)

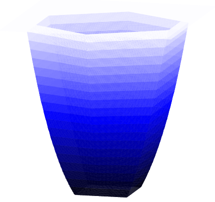


(b)

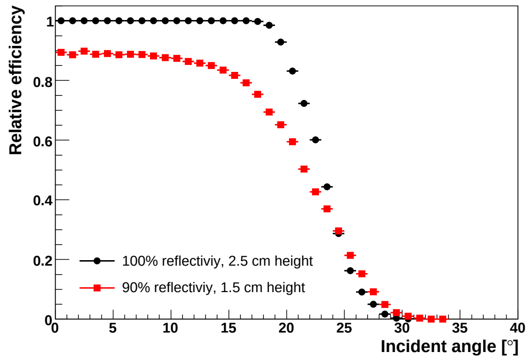
Fig. 3. MC simulated 1000 GeV γ-ray (top) and 1000 GeV proton (bottom) induced showers collected by a 10.5 m^2-mirror. The red (blue) area corresponds to a FoV of 3° (5°), respectively. 2×2 G-APDs are grouped to form a pixel.

To fully contain the shower image, a FoV of 5° is preferred. Furthermore, the camera housing has to be low-weight but for all that robust and water tight to protect the detector against harsh environmental impacts. The housing also incorporates slow control electronics, low voltage and bias regulators as well as a temperature stabilization system. Moreover, a modular design for easy replacement of all components is important to ensure regular operation without prolonged interruptions. To protect the photosensors during daytime, the camera will be equipped with an automatic lid.

Each G-APD will be equipped with a Winston



(a)



(b)

Fig. 4. Shape of the Winston cone light-guide (top) and its efficiency for different reflectivities of the coating and heights (bottom).

cone light-guide [11] to maximize the active area and to shield against large-angle stray light (Fig. 4). The evaluation of the optimal material and the optimization of the Winston cone geometry is still on-going. The first step towards the final design of the camera involves the construction of a first module comprising 144 G-APDs, as illustrated in Fig. 5. The smallest unit is formed by one pixel, consisting of 2×2 G-APDs. The next larger element is the trigger unit made up of 16 G-APDs; nine trigger units constitute a module.

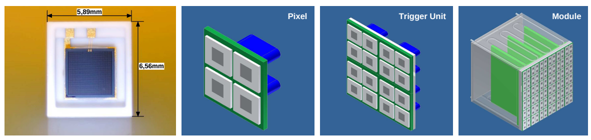


Fig. 5. From left to right: the Hamamatsu G-APD (MPPC S10362-33-100C), layout of a pixel (2×2 G-APDs), a trigger unit (16 G-APDs) and a module assembled of 6×6 pixels (144 G-APDs).

The camera construction will be done in three stages, as illustrated in Fig. 6: a test module (Stage 0) with 1° FoV, an intermediate camera with 3° FoV (Stage 1), large enough to perform γ/hadron sepa-

ration, which will therefore be tested on the Crab nebula TeV source, which is the standard candle for IACTs, and the final camera design (Stage 2) offering a wide FoV of 5° for regular observations. Stage 0 will be mounted on HEGRA CT3 to test the system and to perform measurements of the night sky background as well as to detect first cosmic ray showers. The readout system of the first module is based on existing VME-based electronics. Stage 1 and the final design comprise electronics integrated in the camera housing.

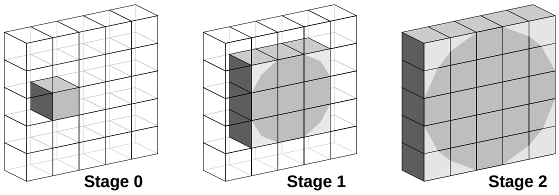


Fig. 6. The camera baseline design.

5. Readout and Data Acquisition System

The analogue signals of four G-APDs of a camera pixel will be linearly added and amplified by dedicated front-end electronics. The summed signals will then be processed by a data acquisition (DAQ) system based on the Domino Ring Sampler (DRS) [12] being developed at PSI for the MEG experiment and used for the MAGIC II readout [13]. A DRS-based DAQ system was already used in part for the first detection of Cherenkov light from extended air showers with G-APDs [8–10].

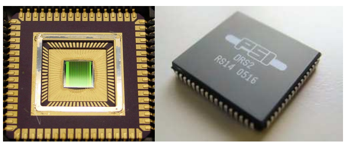


Fig. 7. The DRS chip without and with ceramic package [12].

The DRS is an analogue sampling chip fabricated in a 0.25 μm CMOS process (Fig. 7). It provides 10 pipelines each consisting of a 1024 cell deep array of capacitors. The chip allows for high sampling rates of 1 - 4 GHz, which is crucial for the sensitivity of an IACT. The selection of a very narrow timing window allows the sampling of the analogue signals with efficient suppression of the night-sky background photons [14]. Each analogue pipeline is read out at 40 MHz with an external 12 bit flash analogue-to-digital converter (FADC). The DRS chip has a low power consumption and the integration with the front-end electronics is foreseen with the advantage of less pick-up noise and little signal dispersion. The trigger decision will be based on discriminating the signals of each pixel (2×2 G-APDs) and generating majority information from the trigger units.

6. Conclusions

The novel G-APD-based imaging camera is a small but technologically very challenging project. The realization of the project helps to gain expertise on using G-APDs in IACTs. By installing the camera into the refurbished HEGRA CT3 or an equivalent mount, we will be able to perform the first long-term test of a G-APD camera under realistic conditions. The G-APD camera will have an unprecedent sensitivity and it may therefore be considered as a prototype camera for the next generation IACTs, such as CTA [15].

References

[1] J.A. Barrio et al., MPI Munich, report MPI-PhE/98-5 (1998).
[2] A. Kohnle et al., 26$^{\text{th}}$ ICRC Salt Lake City, Utah, USA, (1999) 239-242.
[3] T.C. Weekes et al., 25$^{\text{th}}$ ICRC, Durban, South Africa (1997) 173-176.
[4] M. Mori et al., Proc. GeV-TeV Gamma-Ray Astrophysics Workshop, "Towards a Major Atmospheric Cherenkov Detector VI Snowbird", Utah (1999).
[5] D. Renker, Nucl. Instr. and Meth. in Phys. Res. A 571 (2007) 1-6.
[6] T. Betz et al., Workshop on Blazar Variability across the Electromagnetic Spectrum, April 22-25, 2008, Palaiseau, France, to appear in Proceedings of Science.
[7] MPPC data sheet of Hamamatsu Photonics: http://sales.hamamatsu.com/assets/pdf/catsandguides/mppc_kapd0002e03.pdf.
[8] A. Biland et al., Nucl. Instr. and Meth. in Phys. Res. A 581 (2007) 143-146.
[9] A.N. Otte et al., 30$^{\text{th}}$ ICRC, Mérida, México (2007), http://arxiv.org/pdf/0712.1592.
[10] A.N. Otte et al., this conference, poster ID 167 (2008).
[11] D. Jenkins and R. Winston, J. Opt. Soc. Am. A 13, No. 10 (1996).
[12] S. Ritt, Nucl. Science Symposium Conference Report 4 (2007) 2485-2488.
[13] R. Pegna et al., Nucl. Instr. and Meth. in Phys. Res. A 572 (2007) 382-384.
[14] D. Tescaro et al., 30$^{\text{th}}$ ICRC, Mérida, México (2007), http://arxiv.org/pdf/0709.1410v1.
[15] CTA collaboration webpages, http://www.cta-observatory.org (2008).